Consistent Research on Solar-Induced Chlorophyll Fluorescence and Various Vegetation Parameters on Inner Mongolian Grassland

Yusi Zhang, Yuhai Bao* and Bayaer Tubuxin
School of Geographical Sciences, Inner Mongolia Normal University, Hohhot, 010022, China

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Abstract: Remote sensing observation of vegetation parameters is a major means of monitoring surface vegetation growth and ecological carbon sequestration. This study adopted multi-years (2007, 2011, 2015 and 2018) of MODIS observed NDVI, EVI and GPP, and SIF dataset (GOSIF) based on OCO-2 observation. Analysis of spatial distribution and temporal variation of regional vegetation and the relationship between various vegetation parameters and GPP was conducted over region of Inner Mongolian. Variation of vegetation parameters on Inner Mongolia grassland is obvious, showing high/low values over the east/west area in spatial, and high/low values during the summer/winter area in time. NDVI, EVI and SIF are well correlated with GPP, and the fitting results in various methods indicates that the consistency between SIF and GPP is optimal (r = 0.909; R^2=0.902). The research shows that direct observation of SIF on Inner Mongolia Grassland is an important parameter for monitoring vegetation carbon sequestration.

1 INTRODUCTION

Photosynthesis is plants' basic metabolic process, and energy and material source of plants growth (Liu, Wu, Zhou, Li, Wang, An, Li, 2017). Sunlight-induced chlorophyll fluorescence (SIF), as the signal released from vegetation chlorophyll, has the potential to directly quantified "actual photosynthesis" (Zhang, Wang, Qiu, Song, Zhang, 2019) to monitor large-scale vegetation phenology (Zhang, Zhou, Meng, Zhang, Liu 2020). Gross Primary Productivity (GPP), as characterization of plant photosynthesis and carbon sequestration, is significant parameter of crop yield assessment and estimate of ecological carbon sequestration (Li, Xiao, 2019).

With the rapid development of SIF monitoring technology, the research on SIF satellite remote sensing in wide area monitoring of vegetation appears in an endless stream in recent years. The inversion of global SIF remote sensing data has been achieved by utilizing China's Carbon Dioxide monitoring satellite, (TanSat), Greenhouse Gases Observing Satellite (GOSAT), Global Ozone Monitoring Experiment-2 (GOME-2) and Scanning Imaging Absorption SpectroMeter for Atmospheric Chartography (SCIAMACHY), Orbiting Carbon Observatory-2 (OCO-2) and other sensors (Zhang, Wang, Qiu, Song, Zhang, Li, Xiao, 2019, Zhang, Zhou, Meng, Zhang, Liu, 2020). Satellite remote sensing observation of vegetation index has been applied to various fields (Su-Jong Jeong, David Schimel, Christian Frankenberg, Darren T. Drewry, Joshua B. Fisher, Manish Verma, Joseph A. Berry, Jung-Eun Lee, Joanna Joiner., 2017), and MODIS product data (like NDVI, EVI, GPP) can monitor vegetation characteristics with large range and long time sequence. Compared with vegetation index, the cloud and soil background have little influence on SIF products with satellite observation, thus it is better to evaluate the photosynthesis of plants (Zhang, Wang, Qiu, Song, Zhang, 2019).

Zhang Jingru (Zhang, Zhou, Meng, Zhang, Liu 2020) and others have probed into the reasons of GOME-2 SIF data pixel time, lower resolution ratio and coverage area affecting the correlation of GPP and SIF by study on comparison of MODIS NDVI, EVI, SIF and GPP of flux tower; Su-Jong Jeong and others (Su-Jong Jeong, David Schimel, Christian Frankenberg, Darren T. Drewry, Joshua B. Fisher, Manish Verma, Joseph A. Berry, Jung-Eun Lee, Joanna Joiner., 2017) evaluated large-scale seasonal phenology and physiology of forest vegetation of high-latitude in the northern in the period of spring and autumn by using SIF, NDVI and GPP from 2009 to 2011; Xinchen Lu and others (Lu, Cheng, Li,

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Chen, Sun, Ji, He, Wang, Li, Tang, 2018) carried out cross-platform inter-comparison to capture the seasonal cycle of canopy photosynthesis by phenological index (PI) and two SIF data sets of OCO-2, GOME-2 and conventional Index (like NDVI, EVI and leaf area index; it is found that the performance of OCO-2 SIF in predicting GPP is better than that of vegetation index and efficiency model of light energy utilization in the global analysis (Li, 2018); Petya K. E. Campbell and others (Campbell, Huemmrich, Middleton, Ward, Julitta, Daughtry, Burkart, Russ, Kustas, 2019) tested the relation between SIF observation of space and time scale and measurement of chlorophyll fluorescence at leaf level (also referred to PSII yield, YII and ETR), gross primary productivity of canopy (GPP) and primary productivity; through research on the influence of drought on vegetation growing by utilizing vegetation index and SIF, it is believed that SIF is likely to be an effective tool to evaluate the influence of short-term drought on vegetation productivity (Tian, Wu, Liu, Leng, Yang, Zhao, Shen, 2019, Liu, Yang, Zhou, Liu, Zhou, Li, Yang, Han, Wu, 2018).

The study adopts global SIF data set (GOSIF) based on OCO-2 newly developed by Xing Li and Jingfeng Xiao. Compared with coarse resolution of SIF data directly collected from OCO-2, the data, with high spatial and temporal resolution (0.05 degrees, 8 days), GOSIF has a better spatial resolution, global continuous coverage and longer time sequence (Li, Xiao, 2019). Compared with AVHRR data, MODIS NDVI and EVI data (MOD13A1) with resolution of 500m and 16 days based on special spatial bands specially used for monitoring vegetation, includes improving sensitivity to reflectance, atmospheric correction and reducing geometric distortion (Huete, Didan, Miura, Rodriguez, Gao, Ferreira, 2002). GPP adopts "semi-empirical" GPP products obtained from MODIS data (MOD17A2H). MODIS-GPP relatively well represents ecosystem level GPP (Running, Nemani, Heinsch, Zhao, Reeves, Hashimoto, 2004), among which NDVI, GPP are calculated according to the measured values of medium resolution imaging spectrometer. Through the research on the relation (International Journal of Remote Sensing, 2020) of vegetation index（NDVI, EVI）in 2007, 2011, 2015 and 2018, Sunlight-induced Chlorophyll Fluorescence (SIF) and gross primary growth (GPP), the capacity of reflecting vegetation dynamic changes of various indexes in study areas is explored to provide reference for deeply understanding the responding of Inner Mongolia Grassland to climate change.

2 DATA AND METHOD

2.1 Study Area

The study area is located in Inner Mongolia Autonomous Region of China (37°24′~53°23′N, 97°12′~126°04′E), short for "Inner Mongolia", situating at northern frontier of China, covering an area of 12.3% of land area. Inner Mongolia Autonomous Region totally includes 9 prefecture-level cities and 3 leagues (Cities of Hohhot, Baotou, Wuhai, Chifeng, Tongliao, Ordos, Hulunbeier, Bayan Nur and Ulanqab; League of Xilingol, Alxa and Hinggan). The whole area is dominated by temperate continental climate with average annual temperature 3~6°C, and the annual temperature and average daily temperature changes greatly, as well as the winter is long and cold, summer is short and warm. The precipitation is rare and unevenly distributed, accounting for 60%~70% of annual precipitation from June to August, and the annual precipitation mainly converging in summer (Li, 2017). Land cover is mainly grassland and desert. The grassland types in spatial distribution is respectively desert grassland in middle and west area and typical grassland in central area as well as meadow grassland in east area of Greater Khingan Range from west to east (Mu, 2013).

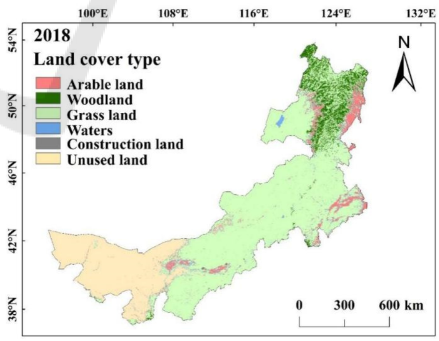

Figure 1: Spatial distribution of land types in study area.

2.2 Data Introduction

2.2.1 Normalized Difference Vegetation Index (NDVI)

Normalized Difference Vegetation Index (NDVI), as one of significant indexes of characterized vegetation coverage level, has been widely applied to regional scale and global scale to understand vegetation growth condition (Guo, Guo, 2021, Li, Zhou, Wang, Shang, Yang, 2019). It is also one of the important indicators that characterize the degree of vegetation coverage and reflect change characteristics of vegetation growth (Piao, Fang, Zhou, Guo, Mark Henderson, Ji, Li, Tao 2003, Mao, Zhu, Wang, Bartel., 2014, Sun, Guo, Yan, Zhao 2010).

2.2.2 Enhanced Vegetation Index (EVI)

Currently, enhanced Vegetation Index (EVI) and NDVI is two frequently-used vegetation indexes to reflect vegetation growth condition, vegetation coverage degree, crop yield and density estimation. By EVI index, NDVI can correct the problem of atmospheric noise, soil background interference and saturation (Chen, Luo, Mo Weihua, Mo, Huang, Ding, 2014, Wang, Liu 2003), thus EVI not only provides new ideas for the research on seasonal change of vegetation with high coverage, but also gives support for the research on vegetation with low coverage (Wang, Liu, Chen, Lin, 2006, Cheng, Huang, Wang, 2005).

2.2.3 Sunlight-induced Chlorophyll Fluorescence (GOSIF)

Photosynthesis is a series of process of luminous energy absorbed by plants absorbed, converted to electricity, among which approximately 1% sunlight energy captured by plants can released by fluorescence mode with longer waves. SIF utilizes oxygen existed in solar spectrum absorbing dark line to perform fluorescence measurement, which shows that it is less impacted by the surrounding background such as soil and environment than other vegetation indexes (LIU, GUAN, PENG, et al, 2012). The merits of SIF method lie in its not needing of precise pulsed and modulated fluorescence technology, chlorophyll fluorescence can directly quantified “actual photosynthesis” (Rahimzadeh-Bajgiran P, Bayaer T, Omasa K., 2017), which is different from the indexes of “potential photosynthesis” mainly observed by “green degree”, like NDVI index. Since satellite inversion of global scale was realized in 2011, SIF remote sensing technology continue to make new contributions to the respects of gross primary productivity of terrestrial ecosystem, global carbon cycle monitoring, phenological and vegetation stress monitoring (Porcar-Castell A, Tyystjarvi E, Atherton J, et al. 2014).

2.2.4 Gross Primary Productivity (GPP)

Gross primary productivity is important components (Yan, Ma, Zhang, Li, Zhang, Wu, Wang, Wen, 2021) of carbon cycle of terrestrial ecosystem, GPP mainly evaluated by daily average of GPP (day) (Zhang, Mark A. Friedl, Crystal B. Schaaf. 2006). Zhang Zhaoying and others’ (Zhang, Wang, Qiu, Song, Zhang, 2019) research results show that there is a good indirect relation between SIF and sunlight and effective radiation, which makes SIF can effectively evaluate GPP in the grassland ecosystem with vegetation productivity mainly decided by chlorophyll content (Guanter Luis, 2014).

Table 1: Dataset from satellites observations used in this study.

Sensor	Data name	Period (year)	Spatial Resolution	Temporal Resolution	References
MODIS	MOD13A1-NDVI	2007/2011/2015/2018	500 m	16 days	Huete et al. (2002)
	MOD13A1-EVI		500 m	16 days	Liu Huiqing (1995)
	MOD17A2H-GPP		1 km	8 days	Running et al. (2004)
	MCD12Q1-LUCC	2018	500 m	yearly	Huete et al. (2011)
OCO-2	GOSIF	2007/2011/2015/2018	0.05°	8 days	Frankenberg et al.(2014)

2.3 Method Introduction

2.3.1 Data Preprocessing

The paper use MODIS NDVI, EVI, GPP in 2007, 2011, 2015 and 2018 as well as land coverage classification data products downloaded from NASA (https://ladsweb.modaps.eosdis.nasa.gov). MODIS NDVI, EVI (MOD13A1) data is synthetic image of 16d maximum value and the spatial resolution ration is 500m; and the GPP data synthesized from the 8-day maximum value of MODIS 1 km spatial resolution ration were also used; as well as land coverage classification data products MCD12Q1, and the spatial resolution ration is 500m.

The study used the global SIF data set (GOSIF) based on OCO-2 researched by Li Xing and others

(Li, 2018), downloaded from University of New Hampshire (http://globalecology.unh.edu/data/GOSIF.html). In line with the batch processing and cutting of vector in the study area, MODIS NDVI, EVI and GPP adopts Maximum Value Composites (MVC) to obtain annual NDVI, EVI, GPP value, which can further eliminate environment disturbance of cloud, atmosphere, snows and sun height angle (Brent N. Holben. 1986). Calculate the average value of annual NDVI, EVI and GPP to generate annual value of NDVI, EVI and GPP of four successive years. The drawing operation is performed after eliminating the invalid value smaller than 0, and the invalid background value.

MCD12Q1 data is the MODIS annual coverage classification production with spatial resolution ratio 500m introduced by MODIS terrestrial research group. Through downloading land coverage classification data in 2018, the data matched with spatial resolution ratio of MODIS NDVI and EVI is generated after preprocessing (Bao, Bao, Qin. Zhou, Shiirev-Adiya. 2013) of projection transform, cutting, resample and category merging by HEG tool, which mainly shows land coverage classification data of parts of arable land, woodland, grassland, waters, construction land and unused land.

2.3.2 Relevance Analysis

Relevance analysis amid four vegetation parameters takes Pearson (linearity) correlation analysis into consideration, and usually the relevant strength of variations can be judged from value range. Formula is as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

2.3.3 Regressive Analysis

The relevance among several indexes is evaluated by multiple regressions of exponential, linear, logarithmic, polynomial and power. Finally, result of the best regression model is presented.

3 RESULTS AND DISCUSSION

3.1 Spatial Distribution of Vegetation Parameter

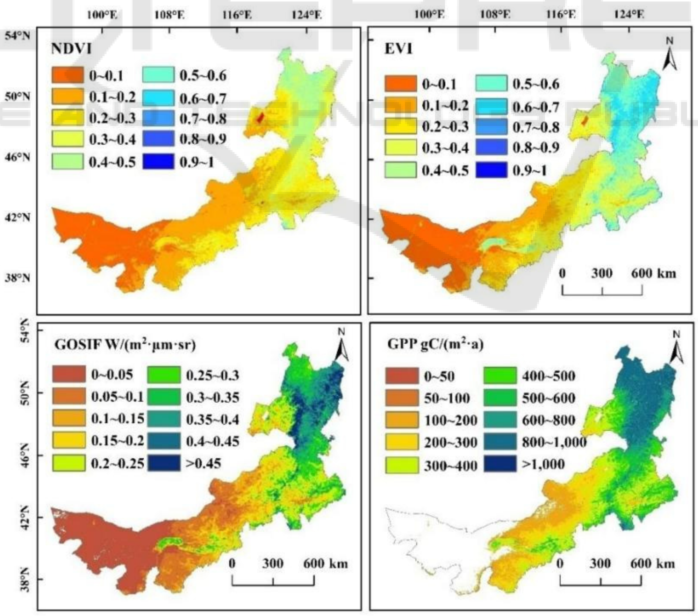

Figure 2: Spatial distribution of the mean value over the years of multiple vegetation parameters.

It can be seen that four vegetation parameters in southwest area of Inner Mongolia are the lowest from the EVI, NDVI, GOSIF and GPP in four years, and four vegetation parameters in northeast area of Inner Mongolia is the highest, as well as the highest value of EVI, NDVI, GOSIF and GPP all appears in Hulunbeier City.

The value range of NDVI in four years is -0.544~0.714, whose mean value is 0.227±0.127; the value range of EVI in four years is 0~0.832, whose mean value is 0.315±0.192; the value range of GOSIF in four years is 0~0.709, whose mean value is 0.224±0.182; the value range of GPP in four years is 45.025~1251.5, whose mean value is 463.771±249.259. On the whole, the value of NDVI, EVI, GOSIF and GPP is higher than other 11 leagues and cities, among which the value in Alxa league is the smallest.

3.2 Time Sequence Distribution over the Years of Vegetation Parameter

As shown in figure 3, annual variations of NDVI, EVI, GOSIF and GPP of four years in Inner Mongolia all presents in pattern of single peak, among which the annual maximum value and minimum value of NDVI in 2007, 2011, 2015 and 2018 is respectively 0.442 and 0.086, 0.490 and 0.0575, 0.481 and 0.115, 0.563 and 0.131; annual mean value is respectively 0.239±0.124, 0.213±0.120, 0.228±0.133, 0.253±0.138. The maximum value and minimum value in 2007 and 2018 appear in first ten days of August and January, the maximum value and minimum value in 2011 and 2015 appears in last ten days of July and first ten days of January.

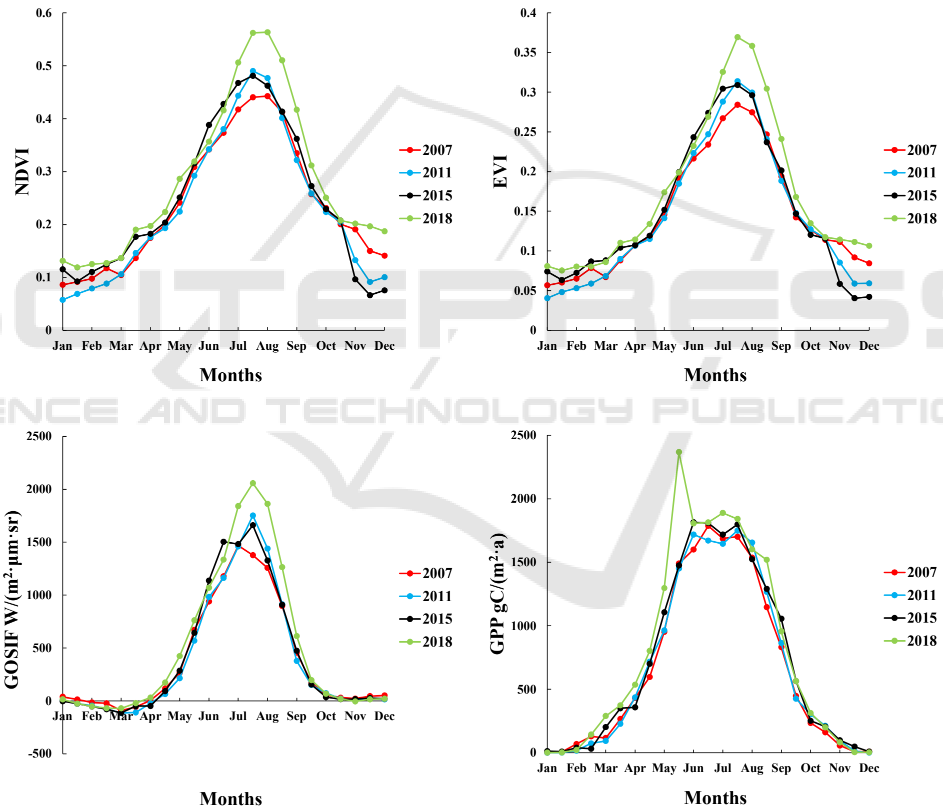

Figure 3: Time sequence distribution of regional mean value of various vegetation parameters.

The maximum value and minimum value of EVI in 2007, 2011 and 2015 is respectively 0.284, 0.0567 and 0.314, 0.0405, 0.309 and 0.0422, 0.369 and 0.0807. Annual mean value is respectively 0.146, 0.144, 0.150 and 0.173. Besides the minimum value in 2015 appearing in the last ten days of December, other maximum value and minimum value respectively appears in the last ten days of July and the first ten days of January.

The maximum value and minimum value of GOSIF in 2007, 2011 and 2015 is respectively 1467.069 and -91.364, 1750.997 and -115.931, 1659.0154 and -113.343; 2056.518 and 70.839; all of them appearing in the last ten days of July and the first ten days of March, annual mean value is 385.135, 383.493, 408.465 and 500.317.

The maximum value and minimum value of GPP in 2007 is respectively 1786.456 and 0.820, appearing in the last ten days of June and the first ten days of January, and annual mean value is 663.551; the maximum value and minimum value in 2011 is respectively 1749.892 and 0, appearing in the last ten days of July and the first ten days of January, and annual mean value is 678.159; the maximum value and minimum value in 2015 is respectively 1797.565 and 9.133, appearing in the last ten days of July and December, and the annual mean value is 716.0637; the maximum value and minimum value in 2018 is respectively 1888.319 and 0.828, appearing in the first ten days of July and the January, and the annual mean value is 801.0210.

The vegetation parameters in Inner Mongolia began to rapidly increase since the mid-month of April, up to a higher value in the first ten days of June, later slowly increasing to the highest value in the first ten days of August. Then the grassland began to become withered and yellow with declining vegetation parameters, until in the late November it returned to the spring and swiftly increased to the previous level.

From the late November to the early April of the second year, the pasture of grassland became withed and yellow and the four vegetation parameters became smaller with a litter changes affected by cold temperature and snowing. The peak season of growth for the grassland in Inner Mongolia is from July to August that is the period with maximum value of NDVI throughout the year.

3.3 Correlation Analysis of Vegetation Index and GPP

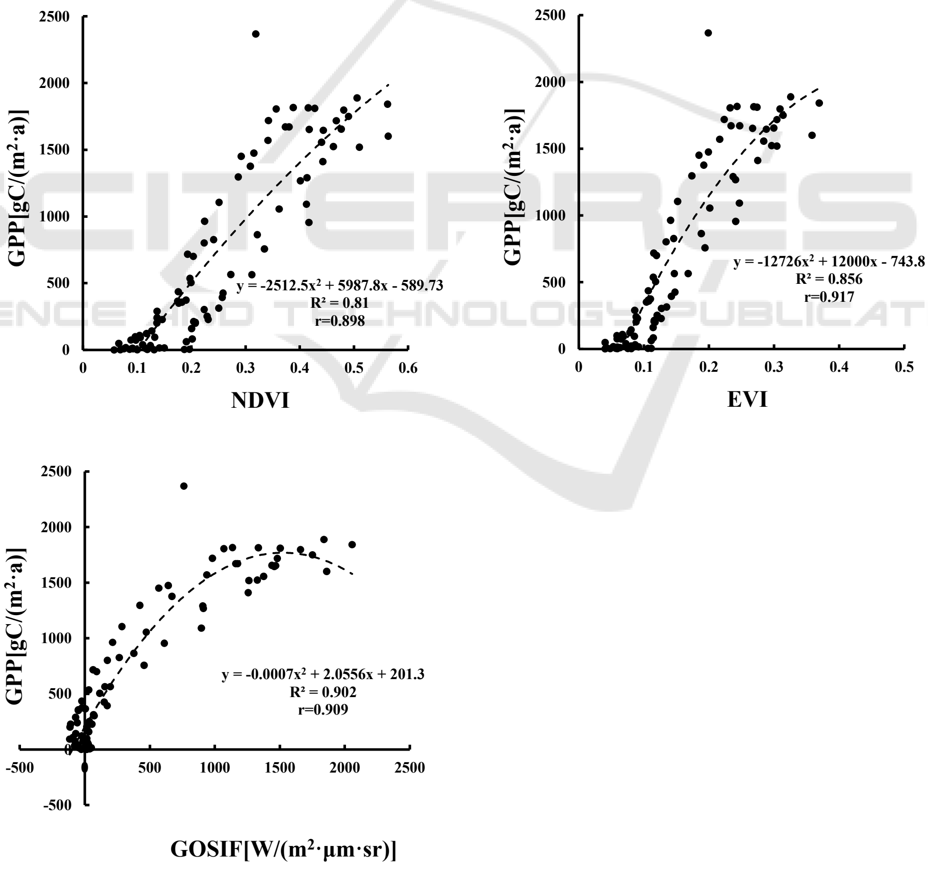

Figure 4: Correlation relation of GPP and vegetation index.

The correlation analysis among four vegetation parameters is performed to show the figure of polynomial regression models with the best correlation relation, the rest of which is listed with detail in the following table. It can be seen that the correlation of GPP and GOSIF is the best, the R^2 is up to 0.902, r is equal to 0.909 with strong correlation; the correlation of NDVI and EVI is the best, the R^2 is up to 0.992, r is equal to 0.994 with strong correlation; the correlation of GOSIF and EVI is the best, the R^2 is up to 0.931, r is equal to 0.960 with strong correlation.

Table 2: Correlation between various vegetation indices and GPP and different fitting results.

Method	NDVI	EVI	GOSIF
Correlation index	0.898	0.917	0.909
Linear fitting	$y = 4549.4x - 433.32$ $R^2 = 0.806$	$y = 7322.0x - 419.62$ $R^2 = 0.84$	$y = 1.0421x + 266.31$ $R^2 = 0.826$
Logarithmic fitting	$y = 1012.0\ln(x) + 2269.7$ $R^2 = 0.749$	$y = 1069.2\ln(x) + 2879.9$ $R^2 = 0.807$	-
Polynomial fitting	$y = -2512.5x^2 + 5987.8x - 589.73$ $R^2 = 0.81$	$y = -12726x^2 + 12000x - 743.80$ $R^2 = 0.856$	$y = -0.0007x^2 + 2.0556x + 201.30$ $R^2 = 0.902$

4 CONCLUSION

With annual changes of various vegetation parameters, the peak season of grassland growth in Inner Mongolia is from July to August, which can represent the annual growth condition of Inner Mongolia. Basically, the vegetation index of grassland in Inner Mongolia began to increase since April, the increasing speed is the fastest in May and it is up to the peak value in August. Then the vegetation activity of grassland began to drop with a decreasing of vegetation index. Affected by climate condition of snowing and low temperature, the vegetation activity of grassland in Inner Mongolia is extremely low from December to March.

Compared with annual change of NDVI, EVI, GOSIF and GPP, four vegetation parameters in Inner Mongolia Region presented a declining trend from east to west with significant different of annual change law, which is mainly affected by distribution difference in Inner Mongolia Region (the east is mainly grassland and the west is mainly desert). Inter annual and intra annual changes trend of mean value amid three vegetation parameters of NDVI, EVI and GOSIF (2007, 2011, 2015, 2018) is close, which all show photosynthetic carbon sequestration capacity of vegetation in some degree (GPP).

The correlation contrast of several parameters in four years show that there emerges good correlation between NDVI, EVI, SIF and GPP (r=0.898, 0.917, 0.909). Various fitting method results show the effect of polynomial fitting is better than logarithmic fitting and the performance is a litter better in fitting, the coefficient of determination R^2 up to 0.90. The result shows that the SIF of the grassland in Inner Mongolia is better to represent time sequence change of GPP and reflects the change law of physiological characteristics of vegetation. The quantity research on SIF and GPP in different regions remains to be further unfolded.

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